$$n_1 = 2K\,(P_A\,/\,P_d)\,/\,CNR = 2(330)\,(15)/50 = 198 \textit{ users neglecting VAD} \tag{3.6}$$

Again, assuming that 60% of the interference comes from users in adjacent cells and including VAD, the number of BCDMA users in the cell (all 3 sectors) is

$$N_{CDMA} = \frac{198}{1.6} \times \underset{\substack{\uparrow \\ \textit{VAD}}}{2} \times \underset{\substack{\uparrow \\ \textit{Sectors}}}{3} = 742 \tag{3.7}$$

Other values for different C/N ratios are readily obtained from Fig 1.2.

3.3 <u>Effect of the AMPS and B-CDMA Base Stations on CDMA Users (Fig. 3.3)</u>

The SNR seen by a CDMA user is given by Eq 2.17. Now however, in the worst case, a CDMA user is in the corner of 3 cells and the power reaching the "worst case" CDMA user from the 3-AMPS base stations is $n_2 P_A$ where

$$n_2 = \underset{\substack{\uparrow \\ 3\ \textit{sectors}}}{(50/3)}\ \underset{\substack{\uparrow \\ 3\ \textit{base stations}}}{(3)} = 50 \tag{3.8}$$

The power received by the "worst-case" CDMA user from each of the 3 B-CDMA base stations is $n_1\bar{P}$.* Each CDMA base station transmits a power of $P_1 = 0.77\bar{P}$ watts/user to two thirds of its users near the base station and the power $1.44\bar{P}$ to the one-third of its users that are far from the base. This constitutes a "coarse" forward power control. Let us also set $P_A/\bar{P} = 9.4$ in the forward direction. Using Eq (2.17) for this worst case condition yields

---

*$\bar{P}$ is the average power received/B-CDMA user.

$$SNR = \frac{1.44 \times 770}{\frac{n_1}{3} + \frac{50}{2}(9.4)} \tag{3.9}$$

Again, for a SNR of 6dB (BER = 10^{-3}), we can determine n_1,

$$n_1 = 127 \textit{ neglecting VAD} \tag{3.10}$$

Including VAD, the fact that the interference is caused by 3 cells, and there are 6 sectors in a cell, the maximum number of CDMA users is

$$N_1 = \overset{\textit{Sectors}}{\overset{\downarrow}{6}} \cdot \underset{\textit{VAD}}{\underset{\uparrow}{2}}n_1/\underset{\textit{Cells}}{\underset{\uparrow}{3}} = 4n_1 = 506 \tag{3.11}$$

Refer to Fig. 3.4. It is readily shown that for the users in the 2/3 area closest to the base station, the SNR is

$$SNR = \frac{0.77 \times 770}{\frac{n_1}{3} + \frac{50 \times 1.6/3}{2}(9.4)} \tag{3.12}$$

Note the 50 x 1.6/3 in the denominator of Eq. (3.12) represents the fact the AMPS base station in the cell is contributing interference to users near the base station and 60% additional interference is coming from base stations in neighboring cells.

Solving Eq (3.12) yields

$$n_1 = 71.7$$

Since the BCDMA interference comes from the CDMA base station in the cell and also an additional 60% comes from adjacent base stations

$$N_1 - \underset{\uparrow \atop \textit{VAD}}{2} \cdot \underset{\uparrow \atop \textit{sectors}}{6} n_1 / \overset{\textit{Adjacent cell} \atop \textit{interference} \atop \downarrow}{1.6} - 7.5 n_1 - 538 \tag{3.13}$$

3.4 Effect of the CDMA Base Stations on AMPS Users (Fig. 3.3)

The SNR seen by the AMPS users is obtained from Eq 1.10:

$$(SNR)_o - \frac{3}{2}\beta^2 \, (CNR) \left(\frac{B}{f_m}\right) \Bigg/ \left(1 + \frac{n_1}{2K}\left(\frac{\bar{P}}{P_A}\right)(CNR)\right) \tag{3.14}$$

Then, with $P_A/\bar{P} = 9.4$ and $K = 330$ and $CNR = 17\text{dB}(50)$, the value of N_1 such that the CDMA interference is equal to the AMPS interference is

$$n_1 - 2K \Bigg/ \left(\frac{\bar{P}}{P_A}\right)(CNR) - \frac{660(9.4)}{(50)} - 124 \textit{ users in the } 3 \textit{ sectors without VAD} \tag{3.15}$$

The maximum number of CDMA users in the cell is then

$$N_1 - 124 \; x \; \underset{\uparrow \atop 3 \textit{ base} \atop \textit{stations}}{\frac{1}{3}} \; x \; \underset{\uparrow \atop \textit{VAD}}{2} \; x \; \underset{\uparrow \atop 6 \atop \textit{sectors}}{6} \; - 496 \textit{ users.} \tag{3.16}$$

3.5 Observations

The results of these calculations indicate that the limitation on the number of users is the interference produced by the BCDMA base stations to a worst-case AMPS user located in the corner of three cells. Even with this limitation, 496 BCDMA users can overlay on top of 50 AMPS users. Thus the combined total number of users in the 10 MHz band become 496 + 50 = 578 users. This result is approximately 11 times the original number of AMPS users using the spectrum.

Note that exactly the same calculations hold for TDMA. In the TDMA case, however, the total number of users is 496 + 150 = 646 which is a factor 4.3 times greater then the original number of TDMA users.

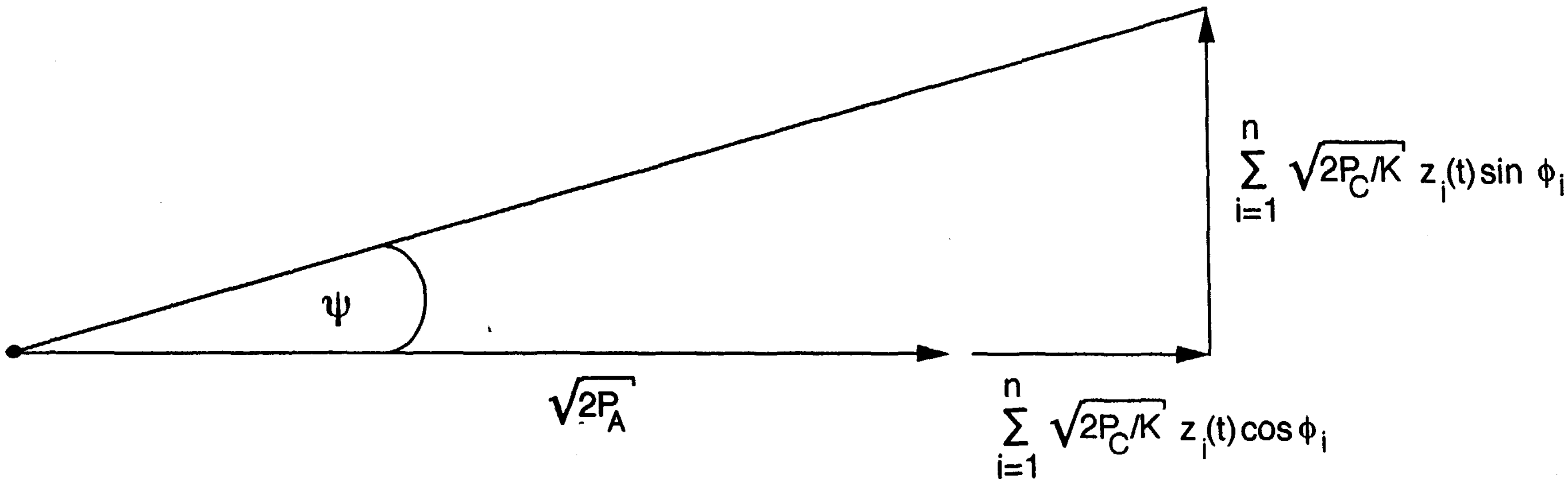
References

[1] Rice, S.O., "Time-Series Analysis," Chap. 25, John Wiles & Sons, Inc., New York, 1963.

[2] H. Taub, D.L. Schilling, Principles of Communication Systems, (2nd Edition), McGraw-Hill, NY 1986.

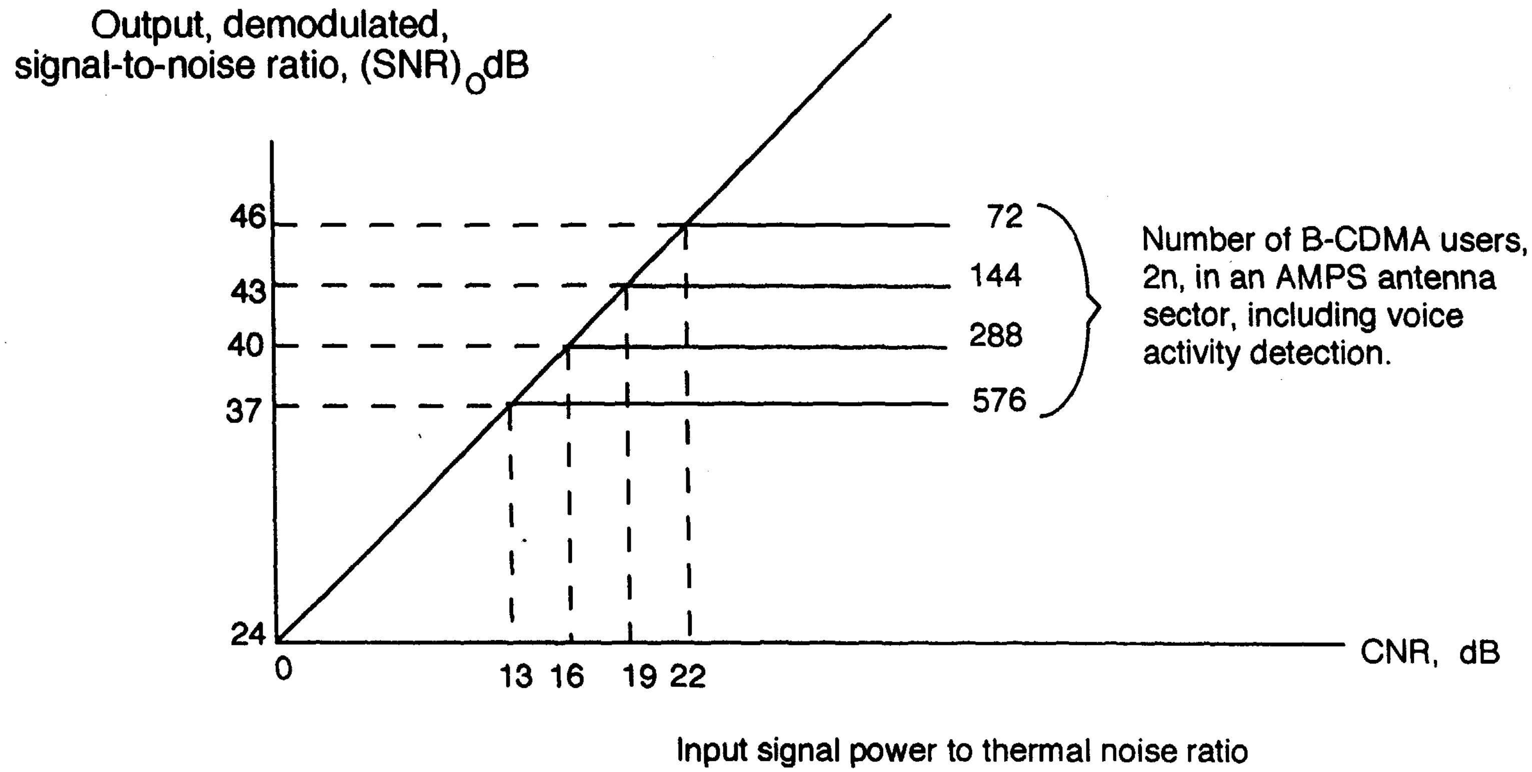
[3] M.B. Pursley, "Performance Evaluation for Phase-Coded Spread-Spectrum Multiple-Access Communication - Part I: System Analysis", IEEE Transactions on Communications, COM-25, No. 8, August, 1977.

[4] J.M. Holtzman, "A Simple, Accurate Method to Calculate Spread-Spectrum Multiple-Access Error Probabilities", IEEE Transactions on Communications, vol. 40, No. 3, March 1992.



Phasor Diagram of an FM Signal With Interference

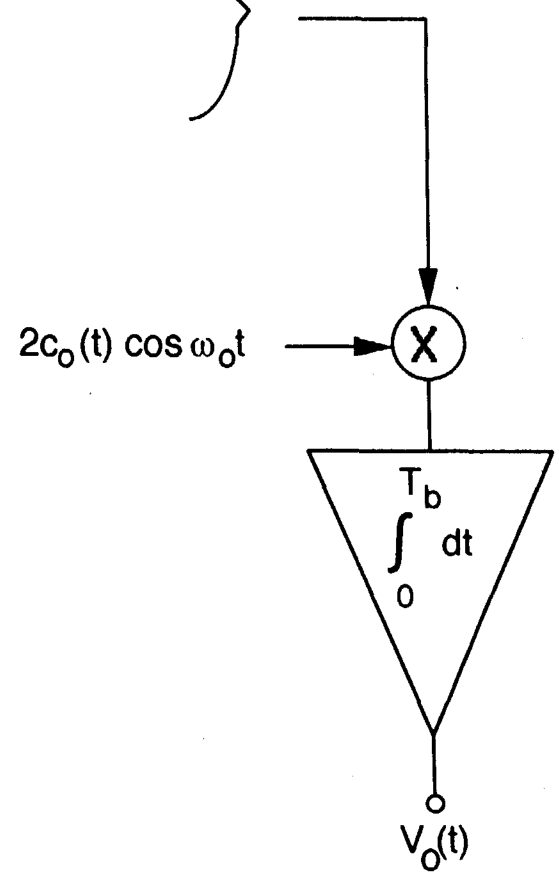
FIGURE 1.1



Output SNR vs. input carrier to thermal noise ratio as a function of the number of users, 2n, in an AMPS sector, when voice activity detection is employed.

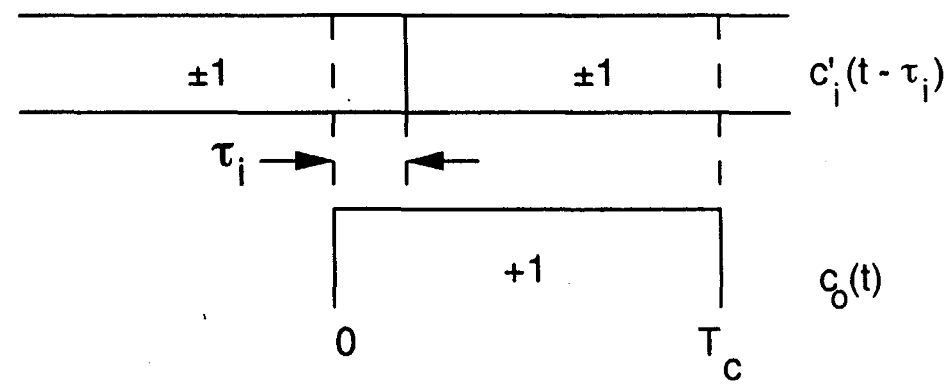
FIGURE 1.2

$$\sqrt{2P_A}\, d_o(t) \cos \omega_o t + \sqrt{2P_A} \sum_{i=1}^{n_1} d_i(t)\, c_i\, (t - \tau_i) \cos(\omega_o t + \theta_i) + \sqrt{2P_I} \sum_{j=1}^{n_2} \cos(\omega_o t + \phi_{mj}(t) + \phi_j)$$



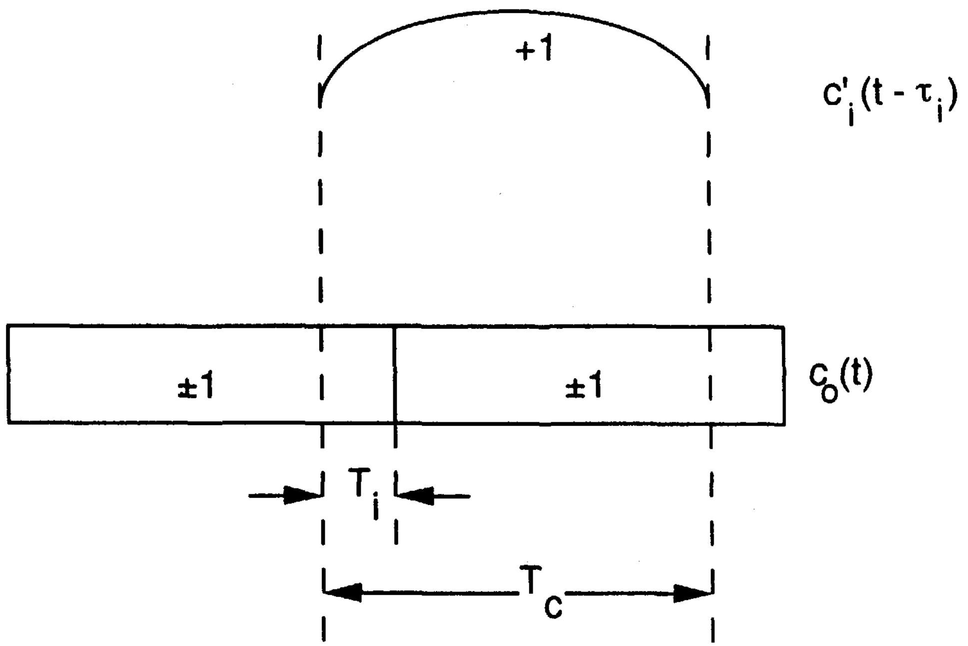
Coherent demodulator for DS/BPSK CDMA in the presence of CDMA and FM interference

FIGURE 2.1



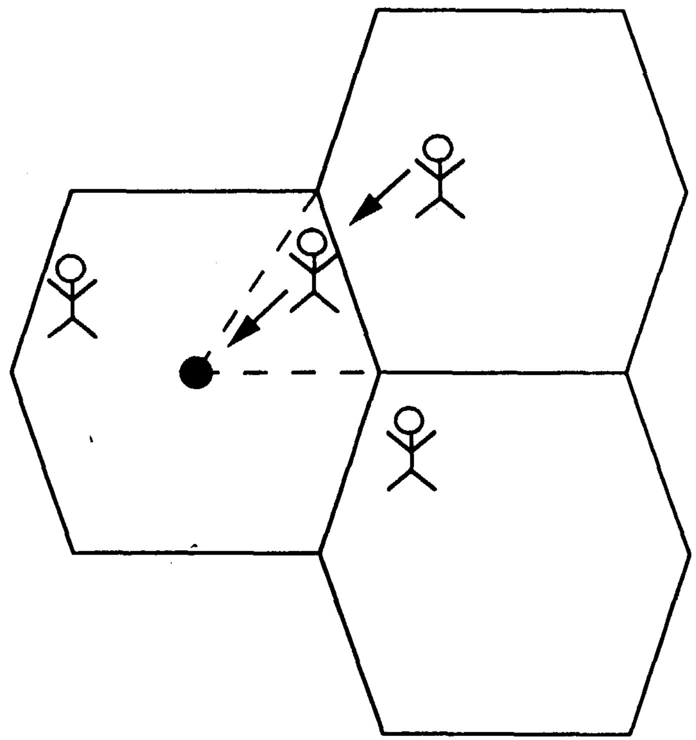
Showing the two chip streams $c_o(t)$ and $c'_i(t - \tau_i)$

FIGURE 2.2



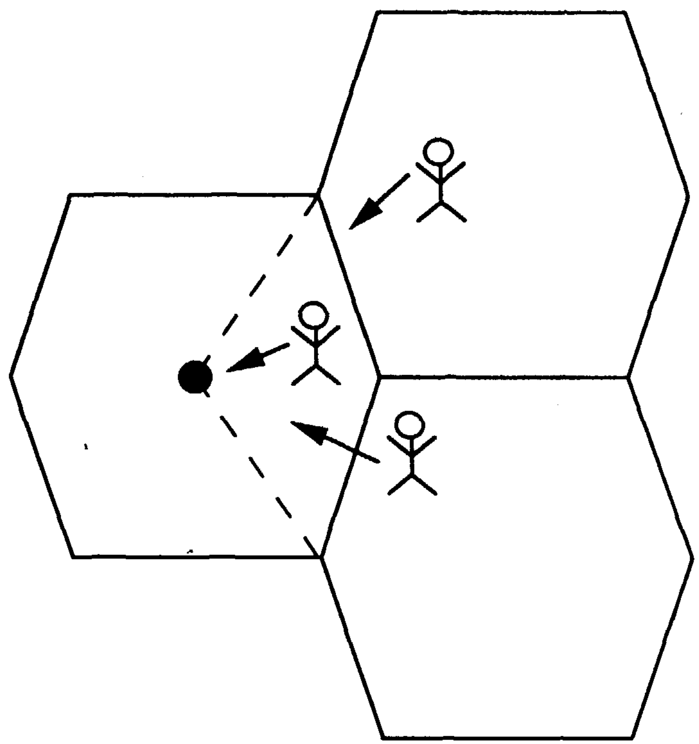
Showing the two chip streams $c_o(t)$ and $c'_i(t - \tau_i)$

FIGURE 2.3



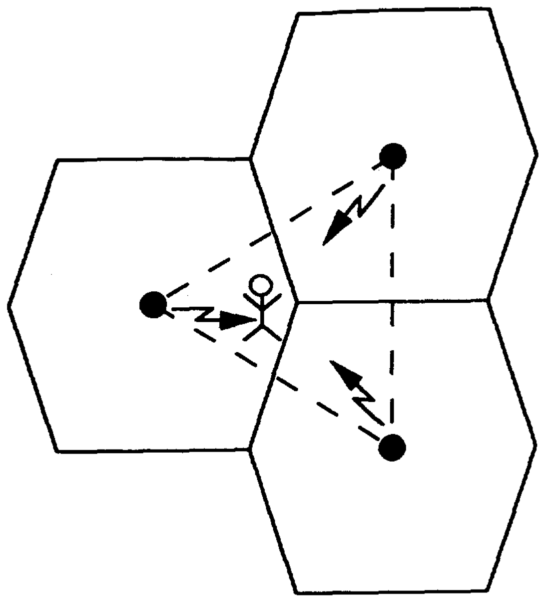
Showing that users in the antenna sector interfere with the base station

FIGURE 3.1

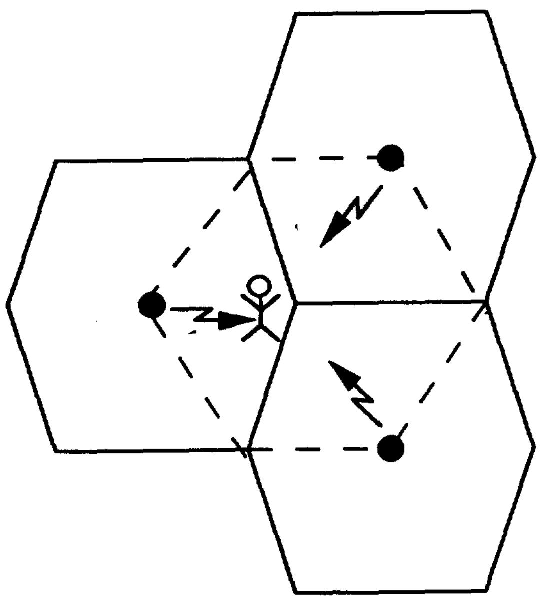


Showing the B-CDMA interference at an AMPS base station

FIGURE 3.2

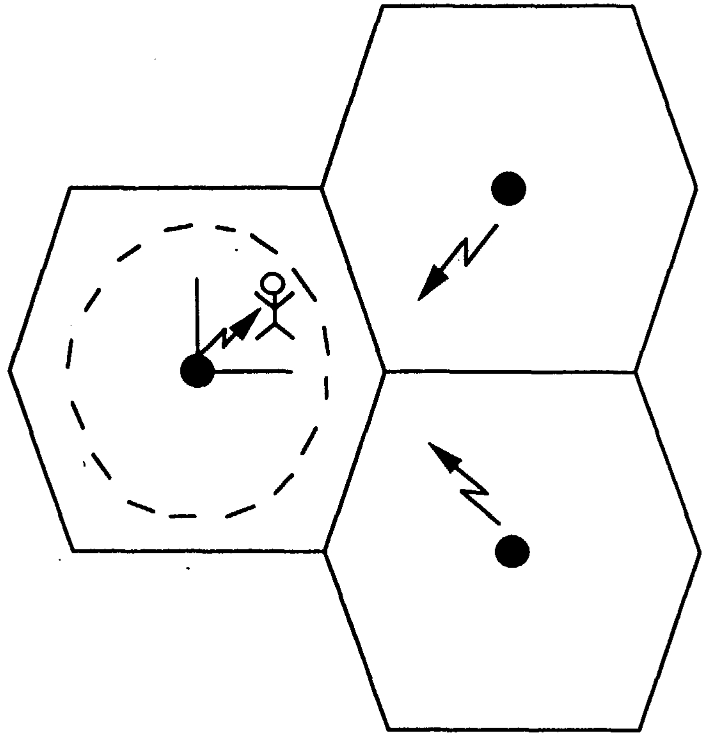


(a) Worst-case user receiving interference from BCDMA base station



(b) Worst-case user receiving interference from AMPS base station

FIGURE 3.3



Showing that in-close users receive interference from base stations in the cell and limited interference from base stations outside the cell.

FIGURE 3.4

APPENDIX C

DYNAMIC CAPACITY ALLOCATION

1.0 COEXISTENCE BETWEEN PCS AND FIXED SERVICE MICROWAVE USERS

The spectral band 1850 - 1990 MHz is the current home of fixed service microwave users (FSMU). These users employ analog or digital modulation techniques and a bandwidth of up to 10 MHz/channel. The FSMU receivers are sensitive to extreme fading conditions and, in an attempt to insure extremely reliable communications, an EIA interference test procedure known as Document 10E[1] was established which prescribed a limit to the amount of external interference.

The interference test required that the transmitter of the receiver under test be powered-down until, for an analog system, the received signal-to-noise ratio, SNR, was 30 dB. The external interference could then be increased until the SNR decreased by 1 dB to 29 dB. In a digital system the transmitter was powered-down until the bit error rate (BER) was 10^{-6}. The interfering power was then increased until the BER increased to 10^{-5}.

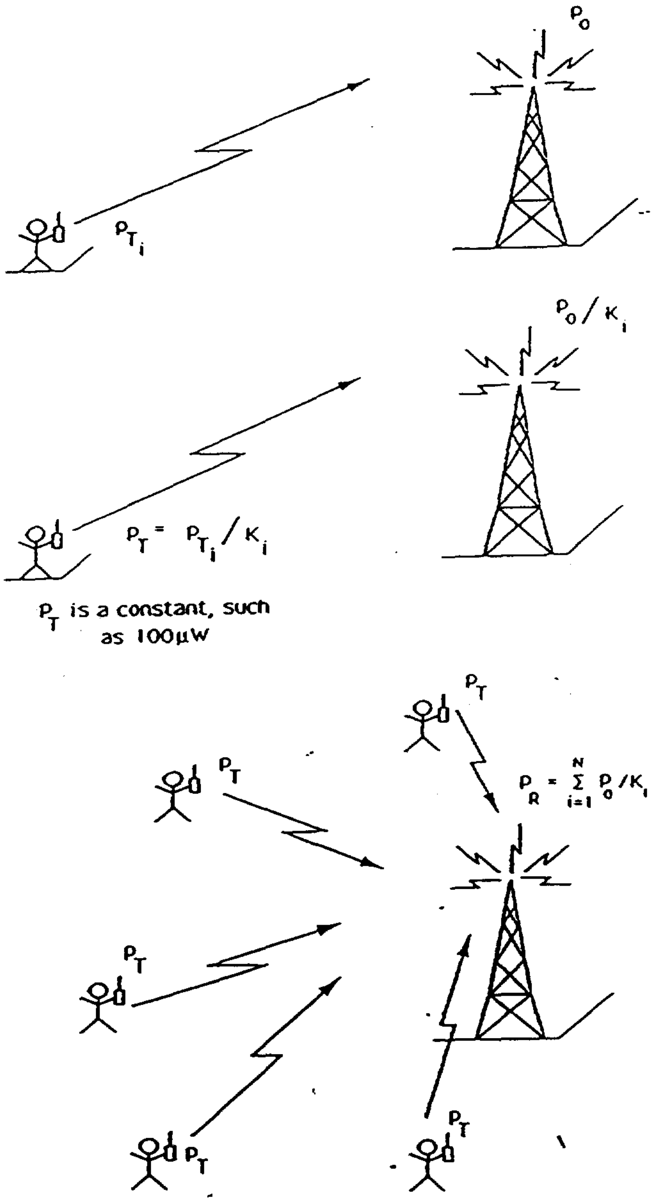
In either situation the power of the interference had to be less than the thermal noise in the test receiver by at least 6 dB.

As a result of the stringent requirements placed on the FSMU, FSMU systems at the same or adjacent frequency bands are required to be spaced far from one another. This causes a significant layout problem with the attendant result that the number of microwave users per square mile is extremely small, when compared to the proposed application of PCS, which is user intensive.

In order to efficiently use the 1850-1990 MHz band, SCS proposed to employ Broadband-CDMA (B-CDMA). B-CDMA was described in our first quarterly report[2] and in numerous published papers.[3,4,5] Making use of the geography and the fact that spread spectrum systems typically operate with a power/unit frequency (power spectral density) which is less than the thermal noise of receiver, the SCS B-CDMA system was shown in tests, performed in Houston and Orlando, with Millicom and the FSMUs, to be capable of sharing the spectrum with the FSMU.

Figure 1.1 outlines the test and analysis procedure. First the FSMU transmitter power was decreased until the receiver had a SNR of 30 dB for an analog system (a BER of 10^{-6} for a digital system). A PCS handset transmitter was then powered-up until a SNR of 29 dB (or a BER of 10^{-5}) was obtained. This maximum received power was called the threshold power P_o and the PCS transmitted power to produce P_o was called P_{Ti}. This experiment was repeated numerous times producing a "grid" of users, each user U_i, when transmitting alone could transmit a maximum power P_{Ti} before thresholding the FSMU receiver.

Using the experimental results obtained in this manner a computer program was developed which normalized the power transmitted per user. Specifically, it was assumed that all cells were of the same



$$P_R = P_o P_T \sum_i 1/P_{T_i} \le P_o \qquad (1)$$

Therefore

$$\sum_{i=1}^{N} 1/P_{T_i} \le 1/P_T \qquad (2)$$

over all users

To avoid interference in accordance with Document 10E.

Equation (2) defines the products of the maximum number of users and the maximum allowable transmitter power per mobile

FIGURE 1.1

radius and all users were assumed to transmit at the same power $P_T = P_{Ti}/K_i$ where K_i is the normalizing factor for each user U_i. Note that the power/user received at the FSMU receiver is now also reduced by K_i to P_o/K_i. The user density was then found (see Fig 1.1) by noting that the power received from all of the PCS users is

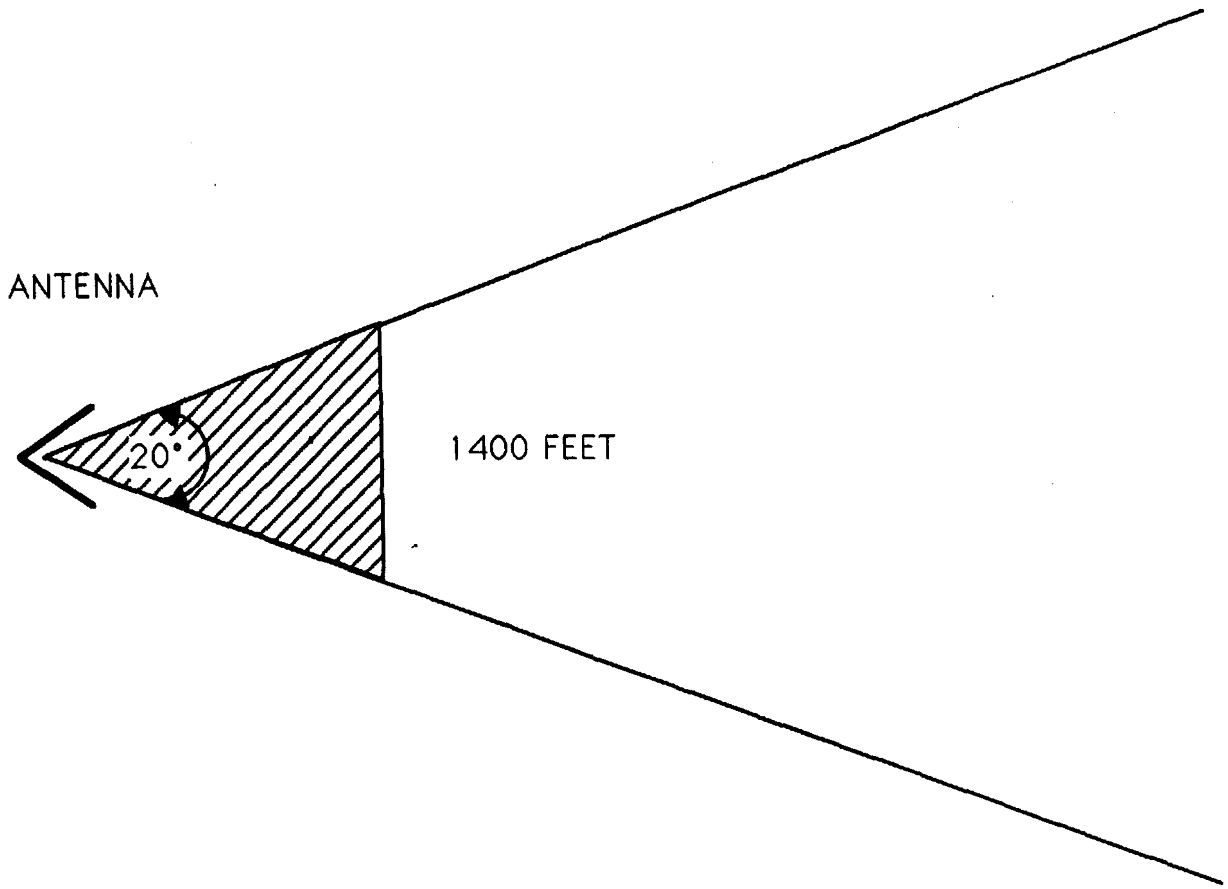
$$P_R = \sum_{i=1}^{N} Po/Ki \qquad (1.1.1)$$

and when $P_R = P_o$, the number of PCS users, N, is a maximum. Hence

$$\sum_{i=1}^{N} \frac{1}{K_i} = 1 \qquad (1.1.2)$$

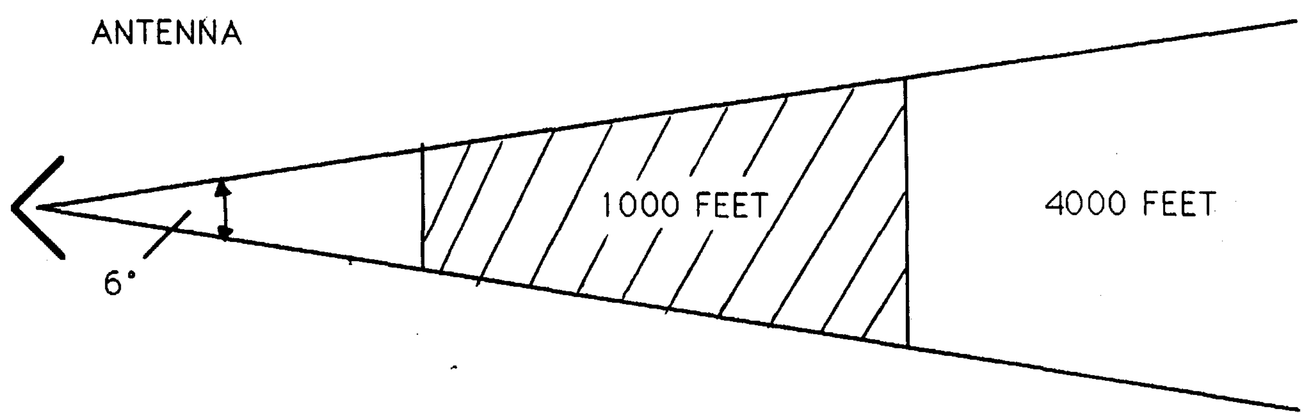
yields the number of PCS users and therefore the user density.

It was found that as a result of the FSMU tower height and the antenna used, PCS users in certain regions affected the FSMU receiver more then in other regions. Figures 1.2 and 1.3 illustrate this point for the measurements made in Orlando and in Houston. Note that assuming a PCS cell to be 1200 feet by 1200 feet (1/20 of a square mile), in Orlando 80% of the interference (i.e., 0.8 P_o) came from users in one-quarter of a cell, i.e., 1/80 of a square mile. Similarly in Houston, 56% of the interference, (i.e., 0.56 P_o) occurred in an area of 60% of a cell, i.e., 1/33 of a square mile.



SHOWING THAT IN THE ORLANDO FIELD TEST, USING AN ANALOG FSM SYSTEM, 80% OF THE INTERFERENCE IS PRODUCED BY PCN USERS LOCATED IN AN AREA OF APPROXIMATELY 0.25 CELLS.

FIGURE 1.2



SHOWING THAT IN THE HOUSTON FIELD TEST, USING A DIGITAL FSM SYSTEM, 56% OF THE INTERFERENCE IS PRODUCED BY PCN USERS LOCATED IN AN AREA OF APPROXIMATELY 0.6 CELLS.

FIGURE 1.3

In order to significantly increase the PCS user density, SCS employed a standard military anti-jam technique - in reverse: When a DS spread spectrum system is jammed by a signal with a relatively narrow bandwidth, the spread spectrum receiver can employ a notch filter to "remove" the interference. In the present application, the notch filter was placed in the transmitter so that the PCS handset would transmit "no" power in the band of the subject FSMU receiver. The notch filter is an inexpensive filter which could employ a varactor diode and is therefore readily tuned to the appropriate frequency within microseconds of a command signal. The strategy proposed by SCS was for each base station to transmit, to the PCS users in its cell, the information needed to tune the notch filter.

Using the notch filter resulted in a significant increase in user density. Table 1.1 compares the user density attained with the notch filter to that achieved without the notch filter. This Table also includes the effect of employing voice activity detection (VAD) circuity which effectively doubles the user density.

Voice Activity Detection (VAD) is readily incorporated into each handset using an Adaptive Delta Modulation (ADM). SCS has performed numerous experiments[6] in this area. The detection technique is also used by COMSAT, etc., to rapidly detect the onset and termination of speech. The VAD operates by sensing the starting and stopping of speech (the technique is also called Time

	Notch & Voice Activity Detection		Notch & Voice Activity Detection	
	# of Users	User Density* (users/sq. mile)	# of Users	User Density* (users/sq. mile)
HOUSTON	108	2,160	23	460
ORLANDO	126	2,520	17	340
NEW YORK CITY	616	12,320	269	5380

Cell Size: 1200′ x 1200′ (1/20 square mile)

P_T (avge): 100 μW

*User Density of the current FDMA system (assuming cell spacing of 3 miles) ≈ 7 users/sq. mile

USER DENSITY PER CELL

TABLE 1.1

Assigned Speech Interpolation, (TASI), or Digital Speech Interpolation (DSI). When the speech stops, the transmitted power is reduced significantly. As a result, the average power transmitted by N users is equivalent to that of N/2 continually "talking" users. The Voice Activity Detector is of no advantage when data or music is transmitted since there are no pauses during transmission. Thus, for data or music transmission there is no significant latter increase in user density.

It is interesting to note that if a speech vocoder other than an ADM is used, forward error correction coding (FEC) must be employed and additional VAD circuitry must be used. Thus, the ADM, an extremely low cost voice coder, is significantly less costly to employ than other proposed coders such as the Linear Predictive Coder (CELP), Adaptive Predictive Coder (APC) or Adaptive Differential Pulse Code Modulation (ADPCM).

2.0 Dynamic Capacity Allocation*

Dynamic Capacity Allocation (DCA) is a monitoring system which is used to insure that there is no excessive interference at a fixed microwave receiver. DCA consists of a sensor module which measures the received fixed microwave signal power and also measures the received PCS interference. Both of these measurements are continually communicated to the relevant PCS

* Patent Pending

base stations. The base station processes the current and past measurements along with the number of users currently accessing that base station in order to determine whether or not to allow additional users to access the base. Furthermore, the base can "shed load", i.e., power down or turn off users if necessary. However, fading occurs in minutes and not in milliseconds and therefore the probability of "shedding" is extremely small.

3.0 B-CDMA Microwave System *

SCS has designed a B-CDMA microwave system which is far less sensitive to interference than the traditional FM or 64-QAM microwave systems currently employed in the 1850-1990 MHz based. Table 1.2 compares a typical 64-QAM microwave system with SCS' proposed B-CDMA microwave system.

Of major importance to the process of coexistence is that the number of fixed microwave users/square mile can be increased by a factor of 10 without being interfered by, or interfering with, the PCS users, providing that SCS' B-CDMA microwave system is employed.

To illustrate the need for a B-CDMA microwave system consider that a PCS handset transmits data at the rate of 32 kb/s, while

* Patent Pending

a fixed microwave system transmits data at the rate of 43 Mb/s, a factor of approximately 1800:1. Thus, each fixed microwave user is equivalent to 650, 32 kb/s PCS users, operating using QPSK.

The capacity of the SCS PCS system with a data rate of 32kb/s and a chip rate of 24 Mb/s is 750. This system's base station can handle up to 500 voice users simultaneously. Using 6, 60 degree sectored antennas in a cell, up to 3,000 voice users can operate in each cell[7]. This result includes the effect of adjacent cell interference.

In a congested area the cell spacing could be approximately 1200 feet apart. Thus, each cell area is 1/20 of a square mile and the capacity of a B-CDMA system is therefore 60,000 simultaneous PCS voice users/square mile. If we assume that the fixed microwave user density is 1 user/square mile (or equivalently 650 PCS users/square mile) it is seen that each microwave user in a square mile uses only 1% of the maximum capacity of a PCS system.